

Ground state sideband cooling of an ion in a room temperature trap with a sub-Hertz heating rate

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Abstract

We demonstrate resolved sideband laser cooling of a single $^{40}\text{Ca}^+$ ion in a macroscopic linear radio frequency trap with a radial diagonal electrode spacing of 7 mm and an rf drive frequency of just 3.7 MHz. For an oscillation frequency of 585 kHz along the rf-field-free axis, a ground state population of $99 \pm 1\%$ has been achieved, corresponding to a temperature of only $6 \mu\text{K}$. For several oscillation frequencies in the range 285 - 585 kHz, heating rates below one motional quantum per second have been measured at room temperature. The lowest measured heating power is about an order of magnitude lower than reported previously in room temperature- as well as cryogenically cooled traps.

Resolved sideband laser cooling of trapped atomic ions was originally proposed with the aim of improving optical spectroscopy [1]. Since the first experimental demonstrations of this technique [2], single ion cooling to the ground state of the trapping potential has been performed both in one- [2] and three-dimensions [3], with a record high one-dimensional ground state population of 99.9% [4]. The possibility of sideband cooling several simultaneously trapped ions [5, 6] has furthermore recently led to a number of outstanding results within quantum information science (See, e.g., [7, 8] and references therein) and ultra-precise ion spectroscopy [9–11]. While narrow ionic electronic transitions may eventually be applied to establish new improved optical atomic clocks, the extreme spectral resolution obtainable with sideband cooled ions enables furthermore fundamental physics investigations, including search for potential time variation of natural constants (e.g., the fine-structure constant [12, 13] and the proton-to-electron mass ratio [14, 15]), and a potential electric dipole moment of the electron [16]. For all the above mentioned applications, uncontrolled interactions between the trapped ions and the environment are key issues for the final quality of the measurements. For instance, fluctuating electrical patch potentials on the trapping electrodes will lead to heating of the ion-motion [17]. A simple model of this effect predicts heating rates which scale roughly inversely with the distance from the ions to the electrodes to the power of four [17], a dependence consistent with experimental findings [18]. For scalable quantum information processing with trapped ions which requires microscopic traps, the only viable solution to this problem seems to be using microtraps cooled to cryogenic temperatures where such fluctuating patch potentials have been found to be dramatically reduced [19]. For spectroscopic purposes where typically only a single coolant ion and a single spectroscopy ion are trapped, an alternative strategy is to employ larger macroscopic traps at room temperature.

In this Letter, we report on one-dimensional ground state sideband laser cooling of a single $^{40}\text{Ca}^+$ ion in a room temperature macroscopic linear radio frequency trap with a radial diagonal electrode spacing of 7.0 mm and an rf drive frequency of just 3.7 MHz. In other words, the trap has an ion-electrode spacing about 3 times larger and an rf frequency nearly a factor of two lower than reported in previous ground state cooling experiments. In this trap, we have demonstrated very efficient cooling ($99\pm 1\%$ final ground state population) and measured motional heating rates over months around one motional quantum per second for oscillation frequencies in the range of 275-585 kHz. These results strongly indicate that

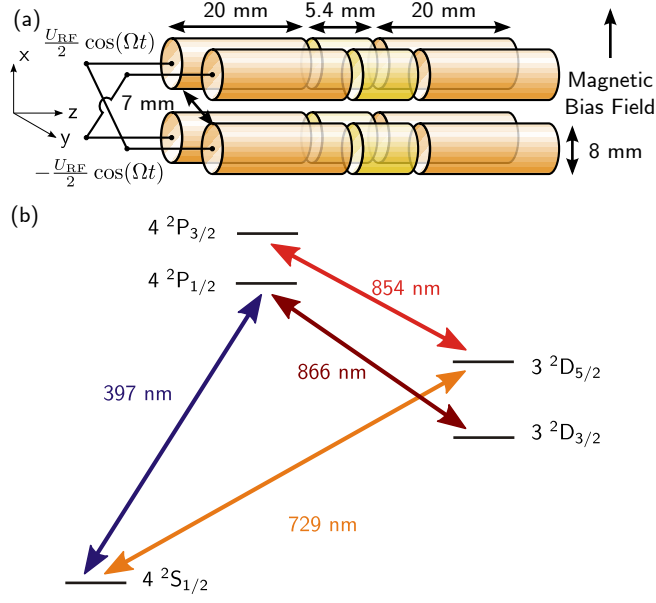


FIG. 1. (a) Sketch of the macroscopic linear Paul Trap including dimensions of and electrical potentials on the electrodes. The electrodes colored redish gold has in addition to the rf potential a dc potential for axial confinement. The orientation of the applied magnetic bias field is also indicated. (b) Reduced level scheme for $^{40}\text{Ca}^+$ with indication of the transitions addressed under Doppler and sideband cooling. For details see main text.

this macroscopic trap at room temperature is very suitable for high-resolution quantum logic spectroscopy due to the long motional coherence time and consequently potentially long interaction times [9]. The zero point energy associated with the ground state cooled ion at these low oscillation frequencies ($\sim 6 \mu\text{K}$ for an oscillation frequency of 275 kHz), make furthermore this trap an interesting tool for investigations of ultra-cold ion chemistry [20]. In this connection, it should be mentioned that we have been able to minimize the amplitudes of the rf sidebands due to uncompensated rf fields to a level corresponding to a residual micromotion energy equivalent to a temperature below $1 \mu\text{K}$ in all three dimensions.

In Fig. 1, a sketch of the linear rf trap (details on the trap design, see Ref. [21]), as well as a reduced level scheme of the $^{40}\text{Ca}^+$ ion with indications of the laser driven transitions are presented. The linear trap consists of 4 segmented stainless steel cylindrical electrodes plated with $5 \mu\text{m}$ gold to which rf potentials are provided in a symmetrical fashion to create an effective radial trapping potential. Axial confinement is achieved through application of an additional dc potential to all eight end-sections of the electrodes. Smaller dc and rf offset

potentials can furthermore be applied to all twelve sections independently to minimize rf micromotion at the effective trap potential center. The rf amplitude can reach 1.5 kV and the dc potentials can be raised to 100 V. For typical single ion experiments, the trap is operated with $U_{\text{RF}} = 1.2$ kV and an endcap potential of $U_z = 20 - 80$ V which result in axial and radial secular oscillation frequencies of $\nu_z = 275 - 585$ kHz and $\nu_{x,y} = 1$ MHz, respectively. In all experiments, a bias magnetic field of 40 Gauss is applied along the x direction. Prior to all sideband cooling experiments, the micromotion is minimized to at least a modulation index below 10^{-1} in all directions (along the quadrupole symmetry axis, the z -axis, it is even compensated down to 10^{-3}) by measuring the Rabi oscillation frequencies on the micromotion sidebands.

A typical experimental cooling cycle starts with a 5 ms period of Doppler cooling by addressing the $S_{1/2} \leftrightarrow P_{1/2}$ transition of the ion with a 397 nm laser beam propagating along the $\frac{1}{\sqrt{2}}(\hat{x} + \hat{y})$ direction, and repumping population out of the $D_{3/2}$ state by a 866 nm laser beam propagating along the \hat{z} direction. This is followed by a 8 ms sideband cooling period comprised of successive pairs of pulses addressing the red sidebands of the $S_{1/2}(m_J = -1/2) \leftrightarrow D_{5/2}(m_J = -5/2)$ transition and the sideband unresolved $D_{5/2} \leftrightarrow P_{3/2}$ transition. The cooling sequence starts with 200 cycles on the 2nd red sideband followed by 200 cycles on the 1st red sideband. Finally, the optical intensity is lowered for another 25 cooling cycles on the 1st red sideband to minimize the effect of off-resonant scattering on the carrier transition. During the whole sideband cooling sequence, every 25 cooling cycles are followed by pulses driving the $S_{1/2}(m_J = +1/2) \leftrightarrow D_{5/2}(m_J = -1/2)$ and the $D_{5/2} \leftrightarrow P_{3/2}$ transitions to avoid trapping in the $S_{1/2}(m_J = +1/2)$ state. (The $D_{5/2} \leftrightarrow P_{3/2}$ and $D_{3/2} \leftrightarrow P_{1/2}$ transitions are always driven together to avoid optical pumping into the $D_{3/2}$ level).

The temperature of the ion is determined by comparing the spectra of the first red and blue sidebands of the $S_{1/2} \leftrightarrow D_{5/2}$ transition using the standard electron shelving technique [4]. In Fig. 2, examples of such spectra are presented for an experiment performed with $U_{\text{rf}} = 1.2$ kV and $U_{\text{dc}} = 80$ V, corresponding to $\nu_z = 585$ kHz. In Fig. 2a, the red sideband spectrum is presented both before and after sideband cooling. After cooling, this sideband clearly vanishes in contrast to the blue sideband presented in Fig. 2b. A suppressed sideband could in principle also originate from population in excited motional states with vanishing coupling or pulses corresponding to 2π rotations. However, with cooling on both the second

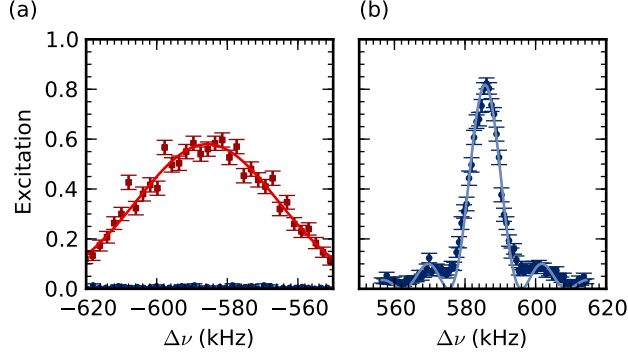


FIG. 2. (a) First order red sideband excitation spectra before (red solid squares) and after (blue solid circles) sideband cooling at an axial oscillation frequency of 585 kHz. (b) Corresponding first order blue sideband excitation spectrum after sideband cooling (blue solid circles). $\Delta\nu$ is the frequency detuning with respect to the carrier. A quantitative analysis of the measured strengths indicates a 0.99 ± 0.01 population of the motional ground state. The presented curves are fits to a Gaussian and Rabi line shape respectively.

and first sideband (the latter at different powers) and the chosen pulse lengths, such potential trapping states are avoided.

A quantitative comparison between the two cooled sideband spectra lead to the conclusion that the ion has an average ground state population of 0.99 ± 0.01 , corresponding to a temperature of $6_{-6}^{+1} \mu\text{K}$.

To gain information on the reheating of the ion in the trap, the red and blue sideband spectra have been compared at different delays after cooling from which the mean occupation number, $\langle n \rangle$, has been evaluated. Results from such measurements are presented in Fig. 3a for trapping conditions identical to those above. As evident from the data, the heating rates are found to be below one quantum per second. The slight off-set from $\langle n \rangle = 0$ at short delays arises from non-optimized initial sideband cooling.

To test whether this low heating rate is particular to the chosen axial oscillation frequency, similar experiments were conducted for other trapping parameters. In Fig. 3b, an extract of these experiments in terms of measured heating rates as a function of ν_z in the interval 275-585 kHz is presented. Obviously, the heating rate seems to be essentially independent on the oscillation frequency and only amounts to one quantum per second, except for the case of $\nu_z = 295$ kHz. The low heating rates have been found to be very persistent, and

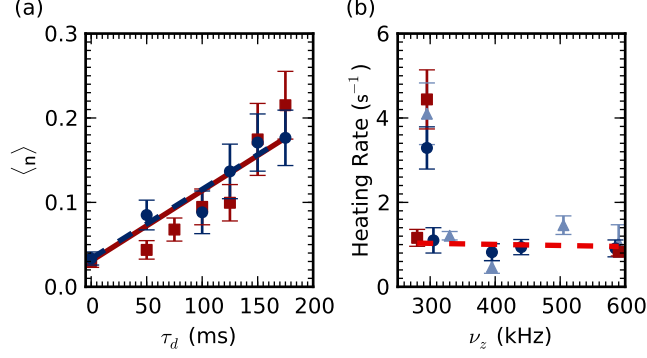


FIG. 3. (a) The mean occupation number of motional excitation $\langle n \rangle$ versus time, τ_d , after ended sideband cooling with an axial oscillation frequency $\nu_z = 585$ kHz. The red solid squares (blue solid circles) represent data point without (with) a mechanical shutter for blocking 397 nm light (see text for details). The solid red and dashed blue lines are best linear fits to the two data sets, resulting in heating rates of $d\langle n \rangle/dt = 0.83 \pm 0.10 \text{ s}^{-1}$ and $d\langle n \rangle/dt = 0.84 \pm 0.05 \text{ s}^{-1}$ (b) Measured heating rates versus axial oscillation frequency. The navy blue circles represent data points obtained the same day, while the light blue triangular data points are obtained during a period of two months. The red squares represents alternative rf voltages to rule out parametric resonances. A constant fit to all data points except the ones at the "resonance" at 295 kHz, gives a heating rate of $1.1 \pm 0.35 \text{ /s}$.

several of the points in Fig. 3b have indeed been measured over months. This includes the resonance at 295 kHz, which has also been proven to be independent of the rf voltage applied, indicating that it is not caused by some particular non-linear resonances due to an imperfect trap [22].

In Fig. 4, our heating rate measurements are compared with ones from other trap experiments on the basis of deduced spectral noise densities. In terms of the product of the spectral noise density and the ion oscillation frequency, our results surpasses previous ones obtained in room temperature as well as cryogenic traps by more than an order of magnitude.

Our measured ultra-low heating rates seem to follow the generally accepted $1/d^4$ scaling, where d is the nearest distance from the ion to the electrodes. The dominating contribution is, however, probably from technical noise and not fluctuating patch potentials, since the measured heating rates are found to be independent of the oscillation frequency [17].

The primary source of motional heating is at present not clear, but a series of experiments

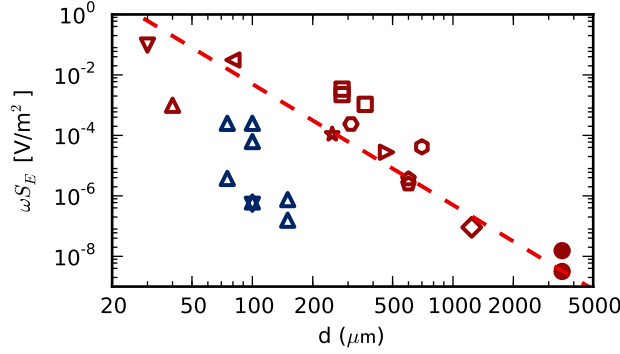


FIG. 4. Heating rate measurements in terms of the spectral noise density multiplied by the oscillation frequency (ωS_E) versus the shortest distance (d) between the ion and the trap electrodes. Previous room temperature (red open data points) and cooled traps (blue open data points) results are presented together with our results (solid dark red circles). Obviously, the value of ωS_E for our experiments with $\nu_z = 295$ kHz are nearly two orders of magnitude lower than previously measured, while at the same time our results generally follow the $1/d^4$ scaling (dashed light red line) expected for fluctuating patch potentials. \blacktriangle $^{24}\text{Mg}^+$, Au [23]; \blacktriangledown $^{111}\text{Cd}^+$, GaAs [24]; \blacktriangleleft $^{137}\text{Ba}^+$, Be-Cu [25]; \blacktriangleright $^{198}\text{Hg}^+$, Mo [2]; \diamond $^{40}\text{Ca}^+$, Mo [4]; \star $^{40}\text{Ca}^+$, Au [26]; \circ $^{171}\text{Yb}^+$, Mo [27]; \circ $^{174}\text{Yb}^+$, Au [28]; \square $^9\text{Be}^+$, Au [17]; \triangle $^{88}\text{Sr}^+$, Ag 6K [19]; \triangledown $^{88}\text{Sr}^+$, Al 6K [29]; \diamond $^{43}\text{Ca}^+$, St. Steel [30]; \bullet $^{40}\text{Ca}^+$, Au

have been conducted to rule out a few. For instance, in Fig. 3a, the two data sets represent two experimental runs with the only difference being the 397 nm light used for Doppler cooling being turned off completely by a mechanical shutter after 15 ms instead of just shut of from a level of 45 mW/cm² by an Acousto Optical Modulator (> 70 dB extinction) for the one set of data. Apparently, the non-completely shutting of 397 nm have no significant influence on the heating rate. Spectrum analysis of the rf and dc source have also been carried out without any indication of resonances in the noise spectrum around 295 kHz (within the 0.5 dB noise level).

Though spontaneous emission in connection with sideband cooling at the low trap frequencies applied in our experiments will lead to heating of the unaddressed motional degrees of freedom, the low heating rates implies that it should be feasible to cool all degrees of freedom to the motional ground state (of a single ion or more) by sequential sideband cooling. Hence, experiments involving a single sympathetically sideband cooled ion in our type of

trap should enable both high-resolution quantum logic spectroscopy of e.g. highly charged [12] and molecular ions [31], and ion chemistry in the ultra-cold regime [20]. With respect to the latter prospect, the low heating rates should additionally make it possible to adiabatically lower the trap potential to reach temperatures lower than might be reached by sideband cooling directly.

The large dimensions of our trap furthermore makes it very versatile as it allows easy introduction of multiple laser beams as well as particle beams without facing the problem of exposing surfaces close to the ions.

In conclusion, we have demonstrated that it is possible to carry out effective ground state sideband cooling in a macroscopic linear rf trap with low rf drive frequencies operated at room temperature. The low heating rates indicate that such trap could be the proper choice for many experiments concerning quantum logic spectroscopy and ultra cold chemistry.

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